instead of continuing on until it cuts the ground, is doubled back and meets it at the point C. This point is to be considered as marking the cold front at the ground. The rate of advance of this point to the right in the diagram, or in other words the speed of the cold air at C in this direction, is the rate of advance of the front. In a typical case, the passage of the whole portion of the cold wedge shown in this diagram would only be a matter of 10 minutes or so. Beyond the left of the diagram the upper boundary of the cold air slopes at a smaller angle still and the rise in pressure consequently proceeds less rapidly.

The various arrows indicate the main features of the air motion in the plane of the diagram, *relative* to the point C—i. e., as they would appear to an observer traveling along C (the velocity of C is to be added at all points to obtain the actual motion). The arrow at D means that the air there is being overtaken by the cold wedge. When the air arrives at E it immediately comes under the influence of the strong pressure gradient and its relative motion is checked or even reversed. It is therefore on the passage of this point that the first sudden change of wind takes place at a ground station.

The squall as measured on an anemogram may be said to have commenced. It continues until a little after the passage of C, when a decrease of wind takes place. The arrow at H indicates that the air there is losing on the front C.

As regards vertical motion, the strong horizontal convergence between D and E necessitates a strong upward current at F. If there is sufficient water vapor present, cloud will form here; and owing to the tendency of the cold air at B to fall, a rolling motion, as indicated, may be imparted to this cloud, which is the characteristic long roll cloud of a line-squall seen in cross section.

On the other hand, the divergence between C and H necessitates a downward current at G. This is in general quite gentle, being spread over a wide area and not concentrated like the upward current at F.

The warm air, having risen over the front edge of the cold wedge, is farther lifted above the upward sloping boundary AB; and, if moist enough, a cloud sheet will form as at N and from this rain may fall through the cold air beneath. The whole system as so far described represents the phase of development of the Aberdeen line-squall of October 14, 1912, of which a detailed description accompanied by cloud sketches has been given by Mr. A. G. Clark in his book on "Clouds."—*A. J. H.*

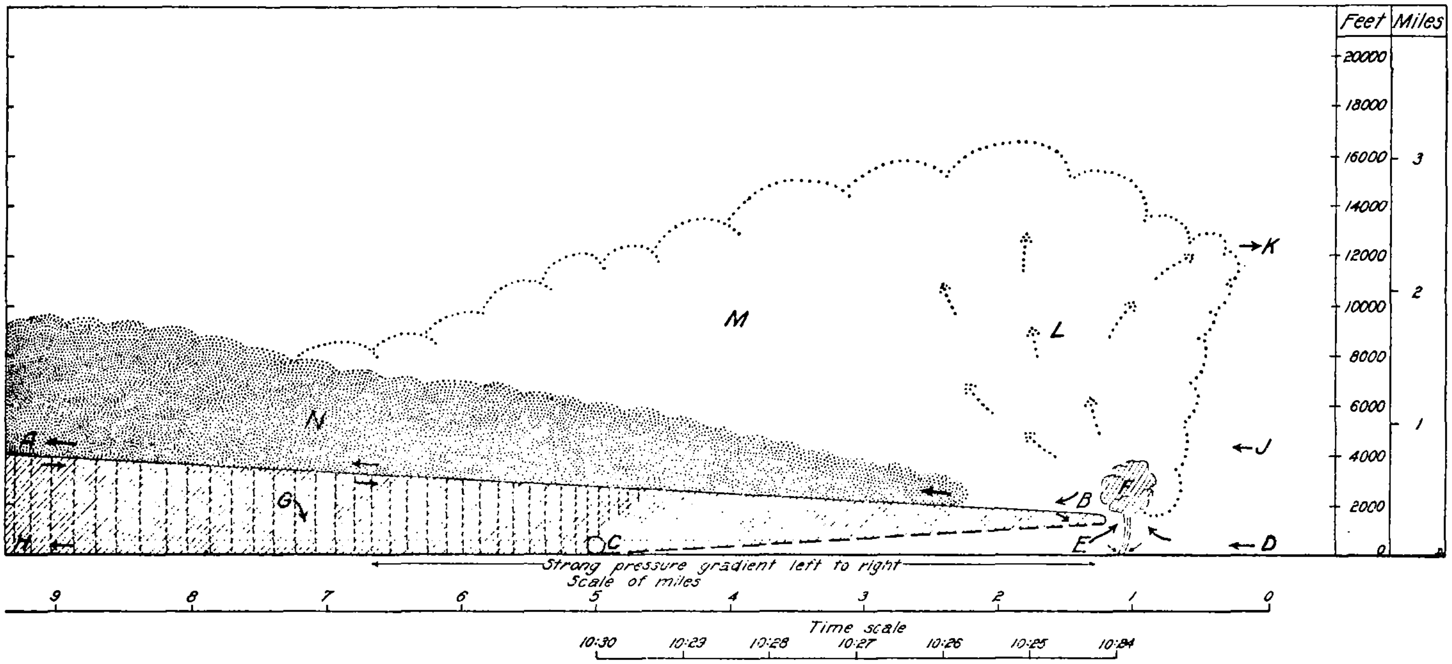

FIG. 6.—Detailed structure of line-squall

HORTON AND GRUNSKY ON THE HYDROLOGY OF THE GREAT LAKES [1]

Abstracted by ALFRED J. HENRY

This volume of 432 octavo pages is replete with hydrologic and related data bearing upon the rise and the fall of the level of the Great Lakes due to natural causes or as the authors put it—the cycle rainfall, run-off, and evaporation. This cycle as related to the Great Lakes invloves the following-named elements:

(1) Rainfall on the drainage basins tributary to the Lakes.

(2) Rainfall on the lake surfaces.

(3) Evaporation from the lake surfaces.

(4) Run-off and inflow into the Lakes.

(5) Outflow from the Lakes.

(6) Lake levels and their fluctuations.

Measurements.—More or less isolated measurements of outflow were made from time to time but it was not until about 1896 that systematic measurements were undertaken by the U. S. Lake Survey. Complete records of lake levels extend back to 1860, and approximate levels can be carried back to 1835. Records of precipitation

[1] Report of the Engineering Board of Review of the Sanitary District of Chicago on the Lowering Controversy and a Program of Remedial Measures, Part III, Appendix II, by Robert E. Horton, in collaboration with C. E. Grunsky, 1927.

from about 1870 onward are available for a number of stations in both Canadian and United States territory within the drainage basin of the Great Lakes.[2]

In general, it has not been possible heretofore to obtain a satisfactory correlation of stage and discharge relations of the Great Lakes with the controlling factors rainfall, run-off, and evaporation for lack of the essential basic data, particularly records of run-off from tributary streams.

Changes or variations in lake level are due to a variety of causes, which may be classed as natural or artificial. Variations due to natural causes include those resulting from variations in rainfall and evaporation, those due to ice conditions and erosion, and transient variations due to barometric changes, wind action, seiches, currents, tides, and waves. Artificial changes include those resulting from channel improvement, control works, and diversion. Variations in lake level may also be conveniently classed as (*a*) permanent, (*b*) secular, (*c*) seasonal, and (*d*) transient. Permanent changes may have resulted from tilting of the lake basins, erosion, and improvement of connecting channels and from diversion. Secular changes are those of long duration, due principally to variations in rainfall and evaporation. Seasonal changes are due to the natural annual cycle of rainfall, run-off, and evaporation and to the effect of ice conditions. Transient changes include those due to winds, barometric variations, seiches, tides, and currents, and in some cases to ice jams.

Aside from the secular changes in natural conditions such as variations in annual rainfall run-off, and evaporation, there have been important geographic changes in the Lake region in recent times. These include:

(1) Deformation or tilting of the land surface, to which attention was called many years ago by the late Dr. Grove Karl Gilbert.

(2) Deforestation and changes in agricultural conditions, particularly the possible effect of the cutting off of the primeval pine forest of northern Michigan.

(3) Deepening and improvement of the lake outlets at control points, particularly on St. Clair and Detroit Rivers.

(4) Artificial diversion from the Lakes.

While it may not be possible at the present time to determine with precision the effects of tilting and deforestation in relation to the hydrology of the Lakes, yet a discussion of these subjects may serve to clarify the situation by showing at least the relative importance or lack of importance of these factors as compared with other factors affecting lake levels and outflow.

Tilting of land surface.—A general tilting of the land surface in the Lake region began in the glacial period and was apparently most rapid immediately following the withdrawal of the ice sheet and continues in some degree at present. It seems probable that at present the deformation of the surface is in the nature of an uplift to the north of a hinge passing near Port Huron and crossing the Lake region in a direction a little north of west. The actual elevation of the outlet of Lake Michigan-Huron relative to sea-level datum is apparently changing but little, if any, at present. * * * Apparently it may be safely concluded that changes in the hydrology of the Great Lakes due to land movement are of little present importance if not wholly negligible, however important they may be locally at certain places around the Lakes.

[2] Cf. Day, P. C. Precipitation in the drainage area of the Great Lakes, 1875–1924. MONTHLY WEATHER REVIEW, March, 1926, 54; 85–106.

Deforestation.—Profound changes in the vegetal cover of the region tributary to the Great Lakes have taken place since 1860, the date when systematic lake-level observations began. These changes have included:

1. Cutting off of the primeval pine forest of northern Michigan and in a large measure the hardwood forests also.

2. Increase in the extent of land under cultivation in the region originally forested in the northern part of the State and a smaller increase in land under cultivation in the southern part of the State. * * * Water losses from regions covered with vegetation are of three kinds:

(1) Interception of rainfall by the leaves and stems of trees or plants and its direct evaporation before reaching the ground.

(2) Transpiration by plants, particularly through the stometal openings of their leaves.

(3) Direct evaporation from the soil.

Interception by well-stocked, mature pine forests is relatively large, amounting to about 25 per cent of the rainfall in regions where the annual rainfall is 30 to 35 inches. The cutting of pine timber in Michigan temporarily reduced the water losses through interception and transpiration, but at the same time it tended to increase the water losses through direct evaporation from the soil.

Water losses from the northern timber region are at present approximately the same as those from a region having a sparse cover of timber and brush. This, accompanied by sandy soil such as prevails in northern Michigan, represents nearly an ideal condition for the conservation of water. The reduced water losses resulting from cutting off the timber in the northern part of the State as compared with the conditions in the southern counties, where intensive agriculture prevails, are reflected in the run-off of the streams, as shown by the following figures:

	Precipitation	Run-off	Water losses
	Inches	*Inches*	*Inches*
Northern region	30	15	15
Southern region	34	12	22

The figures above given for run-off are derived from the averages of numerous gaging records and cover approximately the past 20 years. It will be noted that the stream yield in the northern region is larger than in the southern region, although the rainfall is less.[3]

The excess of water losses for the southern region at present amounts to 7 inches depth on the land surface. Since run-off equals rainfall less water losses, if the rainfall remains the same, the run-off must have been increased to some extent between 1860 and 1895 in the northern region, and it is now probably slowly decreasing as the extent of agriculture increases.

Changes in lake outlets.—For a lake of a given area the lake levels are controlled jointly by—

1. Inflow and inflow fluctuations.
2. The outlet channel capacity at control points.

[3] Grunsky holds that this difference is mainly due to the lower temperature and resulting lower evaporation of the more northerly region, particularly in the summer months, which allows more water to appear there as run-off for the same amount of rain than farther south where summer temperature is higher and evaporation greater. From a study of water losses from drainage basins in eastern United States it appears that the normal decrease of water losses proceeding northward is of the order of 1 to 2 inches per degree of latitude. The center of the northern region in lower Michigan, above considered, is located about 1° north from the center of the southern region. It would appear, therefore, that as regards the variation of water losses with latitude and consequently with temperature and evaporation, the difference between the northern and southern regions of Michigan, other things equal, should be about 2 inches. Instead, the actual difference is 7 inches. It does not appear possible to account for more than about one-half of the observed difference on the basis of differences in rainfall and evaporation combined. There is also evidence of watershed leakage from the north to the south region, which would tend to make the measured yield of the south region greater than the water production of the area.

Owing to backwater effects the controlling factors for Lakes Michigan-Huron operate in a somewhat complicated manner. Beginning at Niagara River the elevation of Lake Erie is controlled by shoals at the head of that river and to a less extent by the crest of the rapids at Niagara Falls. Lake Erie reacts through backwater on the lower Detroit River control in the vicinity of Limekiln Crossing. This in turn operates through backwater on Lake St. Clair. The level of Lake Huron is also controlled jointly by the topography of St. Clair River and by the level of Lake St. Clair.

Under natural conditions before any channel improvements were made there were five principal points of control of the outflow of Lakes Michigan-Huron. The natural bottom elevation at the points of control and the present approximate elevations of the improved navigation channels in feet and tenths above M. S. L. are as follows:

	Natural bottom elevation	Approximate present bottom elevation
	Feet	*Feet*
Foot of Lake Huron	563.0	557.6
St. Clair Delta	571.5	552.8
Head of Detroit River	559.5	552.8
Foot of Detroit River	560.0±	549.8

The crest of the delta of Lake St. Clair had the highest natural elevation and was the principal control. * * * The channel control at the head of Niagara River has been deepened for the improvement of navigation. Changes in channel conditions in Niagara River combined with diversions from this river have operated to increase the discharge capacity somewhat, but their effect is apparently much less important than that of changes in St. Clair and Detroit Rivers. As will be shown, the increased outlet capacity of Lakes Michigan-Huron has drained these lakes into Lake Erie to such an extent as to partly offset the effects of other causes operating to lower Lake Erie levels.

Overflow from Lake Superior has been in recent years completely subject to control by regulating works. Changes in outlet conditions of Lakes Michigan-Huron, i. e., changes in the St. Clair and Detroit Rivers are the most important in relation both to the hydrology of the lakes and to navigation. * * *

In the case of Lakes Michigan-Huron, changes in outlet conditions react slowly on lake levels, which require more than five years for full readjustment. Changes in the outlet of these lakes have long been in progress and the effects of different improvements overlap, so that the final resultant effect on the levels of Lakes Michigan-Huron has not yet been fully realized. Channel changes, diversions and effects of cyclical changes due to natural causes, have been going on together for many years. This makes it difficult to determine separately the effect on lake levels produced by different causes. Various estimates of the effect of channel improvement on the levels of Lakes Michigan-Huron have been made, ranging from 2½ to 8 inches or more. That the actual lowering of the levels of these lakes through uncompensated outlet channel deepening has been at least 8 inches seems now beyond doubt.

Rainfall.—Rainfall data for the Great Lakes region are relatively numerous and complete. * * * Using the rainfall records for Beaver Island in Lake Michigan and the small islands in the Straits of Mackinac as a basis for estimating the relation between rainfall on lake surfaces and that at adjacent land stations, the rainfall on the lake surfaces has been estimated separately from that on the tributary land surfaces, and further the division of the rainfall between winter and summer is shown in the table below:

	Lake Superior	Lake Michigan-Huron	Lakes Erie-St. Clair
On land areas:	*Inches*	*Inches*	*Inches*
November-April	10.12	15.67	16.72
May-October	18.53	18.81	18.33
Total	28.65	34.48	35.05
On water surface:			
November-April	11.44	14.16	14.56
May-October	16.95	17.16	16.33
Total	28.39	31.32	30.89

These figures differ slightly from those of Grunsky owing mainly to correction for snow deficiency and to separation of the rainfall on the lake and the land surfaces.

Evaporation.—In general, the evaporation losses from a water surface depends on several factors, including, in order of their importance, water surface temperature, wind velocity, vapor pressure, and air temperature. In the case of a broad lake a certain proportion of the vapor emitted near the windward shore is carried forward horizontally with the wind close to the water surface, forming in effect a vapor blanket, the effective thickness of which may be very slight but which dominates the vapor pressure in the air above in the control of evaporation.

Air temperature enters as a factor in this case only when it differs appreciably from the water temperature. Records of water temperatures were made at several stations around the Great Lakes by the U. S. Signal Service for the years 1873–1886. Using these data and data for wind velocity and air temperature at the same and other U. S. Weather Bureau and Canadian stations, the evaporation from the Great Lakes has been computed by means of a modified form of the well-known Dalton formula adapted to take into account the effect of the vapor blanket above described. In the table next below will be found a summary of the meteorological data used and the calculated evaporation for the different lakes. The result of the calculation have been checked by comparison with the measured evaporation at certain locations in and adjacent to the Great Lakes region.

Means of meteorological data and evaporation (1874–1875 to 1923–1924)

	Air temperature	Water surface temperature	Wind velocity	Evaporation
Lake Superior:	°*F.*	°*F.*	*m. p. h.*	*Inches*
November-April	19.6	[1] 26.8	5.2	4.23
May-October	54.1	49.2	4.8	11.23
Water year	36.8	38.0	5.0	15.76
Lakes Michigan-Huron:				
November-April	27.6	30.3	5.5	7.22
May-October	58.9	59.1	4.7	22.31
Water year	43.2	44.7	5.1	29.53
Lakes Erie-St. Clair:				
November-April	32.7	33.0	5.2	8.39
May-October	62.1	60.8	4.3	20.90
Water year	47.4	46.9	4.7	29.29

[1] Allowance for ice around lake margins.

Inflow to the Great Lakes.—Records of run-off are available covering 52.1 per cent of the land area tributary to Lakes Michigan-Huron and 36.2 per cent of the area tributary to Lakes Erie-St. Clair. The longer records extend back to 1902–03 or earlier but the records are more numerous and complete for the last 10 years.

The measured streams are generally well distributed over the area tributary to Lakes Michigan-Huron except the east Huron drainage for which records are meager. The available gauging records have been used as a basis of estimating the land surface inflow to Lakes Michigan-Huron and Erie-St. Clair by dividing the drainage basins into subareas each containing at least one long gauging record and applying the measured run-off determined from records in the subareas to the entire subarea. * * * Estimates of run-off for winter and summer have been made and used when necessary. Owing to the complicated hydrologic conditions in the Michigan-Huron Basin the estimated summer run-off is less than actual run-off[4] and that for winter exceeds the actual run-off by about an equal amount. Difficulty in estimating the seasonal run-off from the Michigan-Huron drainage basin results mainly from ground-water conditions. A large part of the summer run-off is derived from ground water stored during winter. * * *

Estimated run-off from land areas tributary to Lakes Michigan-Huron and Erie-St. Clair

Period	Michigan-Huron	Erie-St. Clair
Winter, inches from land area	5.38	8.98
Summer, inches from land area	9.15	3.16
Year, inches from land area	14.53	12.14
Year, cubic feet per second per square mile	1.07	0.90
Year, cubic feet per second	99,121	27,121

Outflow from the Great Lakes.—Lake Huron outflow can not be directly determined prior to about 1900, owing to the varying effect of changes in channel conditions. The mean outflow from the different lakes and for different periods is given in table next following. The figures for St. Clair and Niagara Rivers have not been corrected for Chicago diversion, beginning in 1900, which should be added to obtain the total outflow from the lakes. Where necessary all the records have been corrected for ice obstruction in winter season. The figures given for Niagara River are corrected for diversions into Welland and Erie Canals and for minor power diversions at the International Bridge at Buffalo, N. Y. The discharge of St. Clair River as determined from United States Lake Survey gaugings for the period 1905–1923 is 4 per cent greater than the discharge determined from Niagara gaugings corrected for Lake Erie storage and yield. While the flow estimated from gaugings is probably more accurate for summer, it is subject to more uncertainty in winter due to ice obstruction.

Summary of lake outflow data (not including the discharge of Chicago sanitary canal)

Period	Years	Winter	Summer	Year
		c. f. s.	*c. f. s.*	*c. f. s.*
St. Marys River, 1905–1923	19	65,200	71,600	68,400
St. Clair River,[1] 1905–1923	19	166,700	194,600	180,700
St. Clair River,[2] 1905–1923	19	152,900	193,700	173,500
Niagara River, 1905–1923	19	192,700	210,200	201,500
St. Marys River, 1860–1923	64	71,700	83,500	77,500
Niagara River, 1860–1923	64	199,100	216,500	207,800

[1] U. S. Lake Survey method based on 1912 discharge table.
[2] Niagara method.

CAUSES OF PRESENT LOW LAKE LEVELS

In January, 1925, Lakes Michigan-Huron were more than 4 feet below their levels of 1885. However, as 1885 was near the end of a cycle of wet years, a subsequent drop in levels was to be expected. With the data of inflow and outflow now available it is possible to determine separately the extent to which each of the several causes has contributed to the present low levels.

The authors consider the effect of channel improvement in St. Clair and Detroit Rivers and use three methods to determine the extent to which levels of Lakes Michigan-Huron have been lowered as a result of deepening and improving St. Clair and Detroit Rivers and have deduced from the three methods the fact that the elevation of Lake Huron has been depressed as a result of channel improvement to the extent of at least 8 to 10 inches.

The Chicago and other diversions have lowered the level of these lakes an additional 6 to 8 inches, thus making a total lowering of 14 to 18 inches. There remain, however, 30 to 34 inches to be accounted for. The depression due to a deficiency in precipitation is next considered, and it is found that 15½ inches may be attributed to reduced water production of the Lake Superior drainage basin. Using the figures that they have hereinbefore derived, it is shown that the water production of the Michigan-Huron basin in the period 1880–1884 averaged 124,300 c. f. s. as compared with 90,600 c. f. s. for the years 1920–1923, a decrease of 33,700 c. f. s., and this accounts for 1.69 feet, or 20.3 inches. Reduced water production of the upper lakes is therefore adequate to account for a total lowering of the levels of Michigan-Huron since 1885 of roundly 36 inches. The present depression of over 4 feet in the levels of these lakes is made up as shown in the table next following.

Sources of present depression of Lakes Michigan-Huron

Diversion	6 to 8 inches.
Channel improvement	8 to 10 inches.
Deficient water production:	
Lake Superior basin	13.5 inches.
Michigan-Huron basin	20.0 inches.
Total	49.5 to 53.5 inches.

Several years must elapse before deficiency in supply exercises its full effect on lake levels. The depression due to low rainfall in very recent years has not yet been fully realized, and if present low rainfall continues some further drop in levels will occur. The figures given represent the total drop to be expected from past rainfall deficiency. The total indicated depression is, therefore, somewhat greater than the actual depression of lake levels thus far experienced.

The question naturally arises, Will the rainfall on the Great Lakes drainage basin remain permanently reduced or will it return to a higher level? The longest existing rainfall records show two facts:

(1) Long and apparently irregular, aperiodic, secular variations in rainfall are characteristic of such records.

(2) There is little evidence of a real permanent change of rainfall of an appreciable amount.

In conclusion the authors say:

> These facts are illustrated by the rainfall record of Padua, Italy, and New Bedford, Mass., the latter being one of the longest American records. These both show long irregular cycles of high and low rainfall, respectively. Similar conditions must be expected for the Great Lakes region. The present cycle of low rainfall will sooner or later come to an end, but long cycles of low-rainfall years must occur in the future as they have in the past. When a cycle of higher rainfall years occurs, lake levels will rise, but even if all diversions were stopped and adequate compensation were made for channel improvements a long period of time must elapse before Lakes Michigan-Huron would be restored to their normal levels. The restoration would not be permanent, but cycles of depression would be repeated from time to time, corresponding to cycles of low rainfall. The only complete and adequate remedy is regulation. This is the only means that will provide definite, stable lake levels for all future time.

[4] As determined from measured lake outflow.